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Results of a paired catchment analysis of forest thinning in Turkey in relation to forest management options

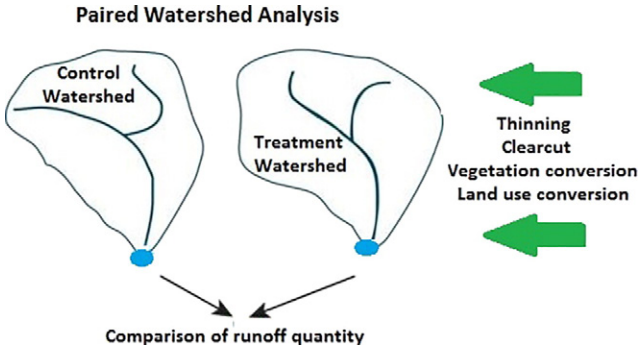
Ibrahim Yurtseven *, Yusuf Serengil, Ferhat Gökbulak, Kamil Şengönül, Süleyman Ozhan, Umit Kılıç, Betül Uygur, Mehmet Said Ozçelik

Istanbul University, Faculty of Forestry, Department of Watershed Management, 34473 Sariyer, Istanbul, Turkey

HIGHLIGHTS

- Climate change management of water-related forest ecosystem services is essential.
- A paired experimental watershed study was conducted over different time periods.
- Two different cutting treatments were applied and the impact on runoff was analyzed.
- Results were linked to global studies on clearcutting, thinning and vegetation change.
- Better water yield depends on precipitation, climate conditions and cutting treatments.

GRAPHICAL ABSTRACT



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ABSTRACT

Adaptation to climate change has become a more serious concern as IPCC assessment reports estimate a rise of up to 2 °C in average global temperatures by the end of the century. Several recently published studies have underlined the importance of forest management in mitigating the impacts of climate change and in supporting the adaptation capacity of the ecosystem. This study focuses on the role of water-related forest services in this adaptation process. The effects of forestry practices on streamflow can best be determined by paired watershed analysis. The impact of two cutting treatments on runoff was analyzed by a paired experimental watershed study in the Belgrade Forest and the results were evaluated in relation to similar experiments conducted around the world. Forest thinning treatments at 11% and 18% were carried out in a mature oak-beech forest ecosystem over different time periods. Although the thinning increased the runoff statistically, the amount of surplus water remained <5% of the annual water yield. Evidently, the hydrologic response of the watersheds was low due to the reduced intensity of the timber harvest. Finally, the results were combined with those of global studies on thinning, clearcutting and species conversion with the aim of formulating management options for adaptation.

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1. Introduction

Ecosystems across the world are under the increasing pressure of anthropogenic stressors (Sicard et al., 2016). This raises concerns for the sustainable provision of some ecosystem services including water

* Corresponding author.
E-mail address: ibrahimy@istanbul.edu.tr (I. Yurtseven).

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production. Climate change is a major threat having potentially serious impacts on the quality, regime and yield of water (Hesse et al., 2015). Furthermore, land-use change or inappropriate land use practices may exacerbate these effects (Pamukcu et al., 2014).

Forests have a well-recognized place in the science and policies related to climate change mitigation, while their place in climate adaptation still needs to be developed. In this respect, better management strategies may boost the capacity of forests further, especially in water-related adaptation issues.

A growing forest not only removes net carbon from the atmosphere, but also provides services (e.g., providing water, purifying the air, regulating the microclimate) that support adaptation. In other words, the carbon removal by the forests is strongly linked (in a positive or negative direction) to the ecosystem services, especially those of water production. Considering that even the most optimistic IPCC AR5 scenario (RCP 2.6) predicts a 1.5–2 °C temperature rise globally by the end of the century (IPCC, 2013), a better understanding is needed of ways in which forests can be made more resilient to climate change while still providing ecosystem services.

The Mediterranean basin that comprises Turkey and a large part of southern Europe lies within one of the most vulnerable regions in terms of climate change (Lionello et al., 2014), making this area susceptible to drought, desertification, water shortage, and floods. In Turkey, the mean annual precipitation drops to 200 mm in semiarid central Anatolia (Asouti and Hather, 2001), while it exceeds 2000 mm in the Black Sea coastal region (Bozkurt and Sen, 2011). Thus, the great variation in the distribution of precipitation across the country in combination with current land use-based problems (desertification, erosion, etc.) may result in a number of water-related concerns in the coming decades.

Adaptive forest management strategies have been proposed to support the climate change adaptation capacity of the forests (Linder, 2000; De Dios et al., 2007) and create more resilient ecosystems (Biggs et al., 2012). Resilience enables a forest to withstand or absorb external pressures and, over time, return to its pre-disturbance state (Rammer and Seidl, 2015). Because of their generally reduced biodiversity, plantations and modified natural forests will face greater disturbances and risk of large-scale losses due to climate change than primary forests (Pawson et al., 2013). Therefore, the resilience of a forest ecosystem is related to its biodiversity, structure, and management. Adequate management approaches must support ecosystem resiliency as well as provision of ecosystem services.

According to Sanz and del Jalón (2005), streamflow parameters can be used to evaluate the response of ecosystems to forestry treatments or disturbances. The aim of this research was to focus on the impacts of selected forestry treatments and investigate their effects on the forest hydrology and closely related adaptation capacities. Hydrology as is a crucial element in the adaptation of ecosystems to changing climatic conditions (Mackey et al., 2008). Precipitation conditions are major determinants of the adaptation capacity of ecosystems. The amount and seasonality of the precipitation are key factors influencing water deficiency in the soil and flood risk (Robichaud, 2016). The overall water cycle in an ecosystem also influences the streamflow pattern, which is vital for riparian habitats (Xiang et al., 2016).

Hydrology is also linked to ecosystem water production. Therefore, forest management operations potentially influence not only the water cycle, but also the water production of the forests, which is an important factor for the local inhabitants. Forestry treatments may also support adaptation by regulating water reduction. Water as a critical issue is more visible in urbanized areas where water demand rises with population growth, resulting in an insufficient supply of available fresh water. Urbanization and urban sprawl are recognized as serious threats to forested watershed functionality and health (Serengil et al., 2012). The low and high flow conditions of streams are especially critical at the point where urban areas and forests converge (Roy et al., 2005). Changes in the seasonal flow pattern may lead to degradation of stream habitats (Belmar et al., 2013), increased frequency of floods (Ouarda et al., 2006), and prolonged low flows (Laaha and Bloschl, 2006).

Forest management is a significant tool for facilitating forest adaptation to climate change and generating ecosystem services. Adaptive forest management has been suggested in order to establish a more flexible approach (Stankey et al., 2005), but there is a need for more understanding of and reliable data on the impacts of sequential management applications. This is problematic, as forest hydrology research around the world is limited because these studies require extensive time, funding and effort.

In brief, adaptive resource planning should be applied in order to achieve the highest possible adaptation level under changing social, economic and ecological conditions. The concept of resource management has been developed to improve management and planning approaches according to the results of collected and analyzed data. In this study, the objective was to evaluate the impact of forestry treatments on streamflow, and by integrating the findings with worldwide hydrological studies, to develop forest management policies that will enhance adaptation capacities.

2. Material and methods

2.1. Study area

The paired watershed methodology is a well-established research approach for analyzing the impacts of various treatments on streamflow by eliminating the influence of variations in climatic conditions (Gökbulak et al., 2016; Serengil et al., 2007; Ssegane et al., 2015). The Ortadere paired experimental watersheds (W-I and W-IV) located in the Kurtkemeri forestry district of the Belgrade Forest have been instrumented and studied for long-term ecological research since 1977 (Fig. 1). The Ortadere experimental watersheds are approximately 3 km south of the Black Sea and 10 km north of the Bosphorus. Precipitation, runoff, and water quality have been monitored continuously since 1978.

The experimental watersheds are covered with native deciduous tree species including oak (*Quercus petraea* L., *Quercus frainetto* Ten.), beech (*Fagus orientalis* L.), hornbeam (*Carpinus betulus* L.), chestnut (*Castanea sativa* M.), alder (*Alnus glutinosa* L.) and rowan (*Sorbus torminalis* L.). Watershed-I (W-I), with an area of 71.9 ha, was kept as the control, while Watershed-IV (W-IV), with an area of 77.5 ha, was used as the treatment watershed. The average crown closure is about 95–100% within both watersheds and the average slopes of the paired watersheds are respectively 10% and 14%. According to Özhan (1977), soils in the watershed are Vertic Xerochrept mainly derived from Neogene loam and gravel deposits. The soil texture of the surface horizon is loamy clay with high erodibility potential and medium permeability. The average depth of the mull-type forest floor is 5 cm, with high detention and retention capacity, providing a buffering effect against overland flows (Balcı et al., 1993). Thus, the streamflow in this forest ecosystem produces hydrographs. The topsoil in the watersheds is approximately 30 cm deep and consists of 3.2% organic matter, whereas this value is 4.9% in the Belgrade Forest where the experimental watersheds are located (Özhan, 1977). Both watersheds were instrumented with V-notch weirs equipped with automatic flow recorders.

According to the Thornthwaite classification system, the climate of the watersheds is humid, mesothermal and oceanic with a moderate water deficit in summer (Balcı et al., 1986). The mean annual precipitation is 1050 mm with a large portion generally falling from October to March. The average temperature is 12.8 °C. The share of snowfall in the annual water yield represents <3% and thus, is not a significant component of the water budget. The streamflow reaches peak values between January and March, depending on the interannual precipitation pattern.

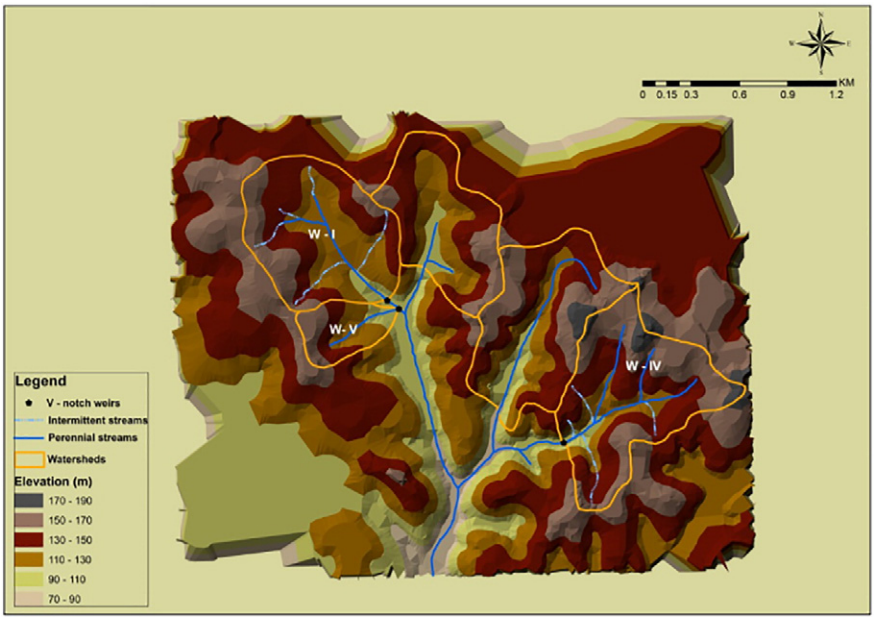

Fig. 1. The location of the paired watersheds.

2.2. Methods

The experimental catchments have been subject to several hydrological and hydrochemical projects since the 1980s and their results have been published (Balcı et al., 1986; Gökbulak et al., 2016; Özhan et al., 2010; Serengil et al., 2007). However, none of these studies compare the hydrological results of two different thinning operations from the perspective of climate change.

This study is based on detection of the influence of treatments on the streamflow at different times by using paired watershed analysis. In February 1986 and from October 2011 to December 2011, 11% and 18% of the standing volumes, respectively, were removed from the treatment watershed (W-IV). Watersheds I and IV were monitored from January 1980 to January 1989, and from January 2006 to December 2015, respectively. The duration of the research was divided into two periods: calibration and post-treatment. Regression equations for the streamflow data of the control and treatment watersheds were developed during the calibration period. The impacts on streamflow of the 11% and 18% thinning treatments were compared with the control watershed by using regression (calibration) equations. The datasets for this study are summarized in Table 1.

The experimental watersheds were monitored for several years (calibration periods) before the treatments, after which 11% and 18% of the standing timber volume were removed from the treatment watershed (W-IV) at different time periods. The standard selective cutting method used was a regular timber harvesting procedure carried out according to the management plans of this forest area.

Water levels in the outlets of the watersheds were recorded using Elliott round-chart recording systems that measure streamflow at 10-min intervals. The raw data was then converted into monthly data to find the mean monthly flows.

Linear regression equations were developed for the streamflow data of the control (W-I) and treatment (W-IV) watersheds during the calibration periods at 95% confidence limits. The calibration equations were used to determine the effect of the timber harvest on runoff.

Table 1
Datasets and study periods.

Treatments in W-IV (treatment watershed)	Time periods	No. of months
Calibration period	January 1980–January 1986	73
11% thinning	February 1986	1
Post-treatment period	March 1986–December 1989	46
Calibration period	January 2006–September 2011	60
18% thinning	October 2011–December 2011	3
Post-treatment period	January 2012–December 2015	48

3. Results and discussion

3.1. Belgrade Forest experiments

The streamflow and precipitation data were evaluated for the pre- and post-thinning periods. Table 2 shows the average monthly streamflow and precipitation data for the treatment (W-IV) and control (W-I) watersheds.

Generally, precipitation was higher than average for all hydrologic years during the pre- and post-treatment periods (Table 2). The precipitation amounts during the pre- and post-treatment periods influenced the magnitude of the response (Hornbeck et al., 1993). Fig. 2 shows the distribution of the monthly streamflow and precipitation values.

As seen in Fig. 2, the high-precipitation months in the region were from November to April, while streamflow peaked between January and March. The monthly streamflow responded to precipitation with a short lag time in the winter months, but was less responsive during the dry summer months. According to Serengil et al. (2007), the lag between rainfall and streamflow can be determined by a correlogram technique, and they suggest that the streamflow amount for a specific month is significantly affected not only by the precipitation of the month in consideration, but also by that of the previous four months. Generally, the soil water deficit began in April and continued until November, and high correlations between rainfall and runoff were found from November to the end of March due to the water surplus in the soil.

The differences between the observed and predicted values representing the effect of the treatment are presented in Table 3. The average monthly streamflow in 1988 was twofold higher than in 1986. The greatest difference after the 11% thinning treatment occurred in 1988 (3rd year) with 5.99 mm, followed by 1986 (1st year) with 5.77 mm. This explains the high 1988 streamflow and the higher difference in measured and estimated flows. Since the flow data did not show normal distribution, a log transformation was performed on the data

Table 2
Average monthly flow (mm) and precipitation (mm) with confidence intervals (CI) during the calibration and treatment periods.

Thinning intensity - period	W-I (control watershed)			W-IV (treatment watershed)			Precipitation		
	Average flow (mm)	SE W-I	95% CI (upper/lower)	Average flow (mm)	SE W-IV	95% CI (upper/lower)	Average (mm)	SE	95% CI (upper/lower)
11% - overall calibration period	26.56	0.34	14.98/ 38.15	32.27	0.4	18.88/45.66	98.41	0.58	77.37/116.97
11% - overall treatment period	13.39	0.35	5.86/18.33	21.15	0.45	10.90/27.32	79.32	0.78	59.18/101.22
1st year	6.42	0.28	1.43/11.41	15.86	0.82	1.03/30.68	54.89	2.05	17.71/92.06
2nd year	20.44	1.21	1.20/39.68	29.61	1.64	3.53/55.68	111.52	3	63.68/159.35
3rd year	23.24	2.21	−11.90/58.38	34.6	2.62	−7.18/76.38	88.97	3.74	29.32/148.60
4th year	2.29	0.09	0.93/3.66	3.65	0.19	0.69/6.61	57.83	2.06	25.06/90.60
18% - overall calibration period	17.05	0.23	9.97/24.13	18.7	0.24	11.31/26.09	80.07	0.61	18.87/45.66
18% - overall treatment period	14.01	0.17	9.36/18.65	17.6	0.24	11.07/24.12	76.91	0.6	9.18/33.12
1st year	15.26	0.76	3.22/27.29	20.03	1.13	2.02/38.03	84.15	2.6	42.80/125.49
2nd year	9.86	0.56	0.94/18.78	10.8	0.65	0.50/21.09	49.7	1.16	31.18/68.22
3rd year	13.23	0.55	4.51/21.95	21.17	0.97	5.69/36.64	101.26	2.74	57.58/144.94
4th year	17.69	0.77	5.42/29.96	18.39	0.93	3.59/33.19	72.54	2.15	38.25/106.83

SE: standard error; CI: confidence interval.

prior to statistical analyses. However, the results presented in the paper are based on the original data.

In Table 3, the positive slope values show an increasing streamflow trend for all the regression equations. In order to determine the relationships between the measured and estimated values statistically, regression equations were developed and the coefficient of correlation (r) was calculated for both treatments. The linear regression equations were used to compare the measured and estimated values of flow throughout the treatment period and the coefficient of correlation was used to compare the effect of different intensities of thinning statistically. Table 3 shows that the coefficients of correlation were high except for the fourth year of the treatment period after the 11% thinning. Generally, the high coefficients of correlation were not statistically different between the measured and predicted values. Decreases in the coefficients of correlation signified statistical differences in the flow. The results indicated that the difference values for all years fell within the 95% confidence interval of the regression line for the treatment period. The differences of lower and upper confidence intervals were increased due to variation of streamflow. As all difference values remained within the confidence interval, there was no significant difference seen between measured and predicted values. Therefore, timber removal rates of 11% and 18% did not statistically increase the water yield.

The Durbin-Watson (DW) test was used to detect the presence of an autocorrelation in the residuals of the regression models of both thinning intensity and time period. The DW scores were generated using the sample size and k coefficient. According to the DW test results, autocorrelation was not found in the residuals. According to the regression

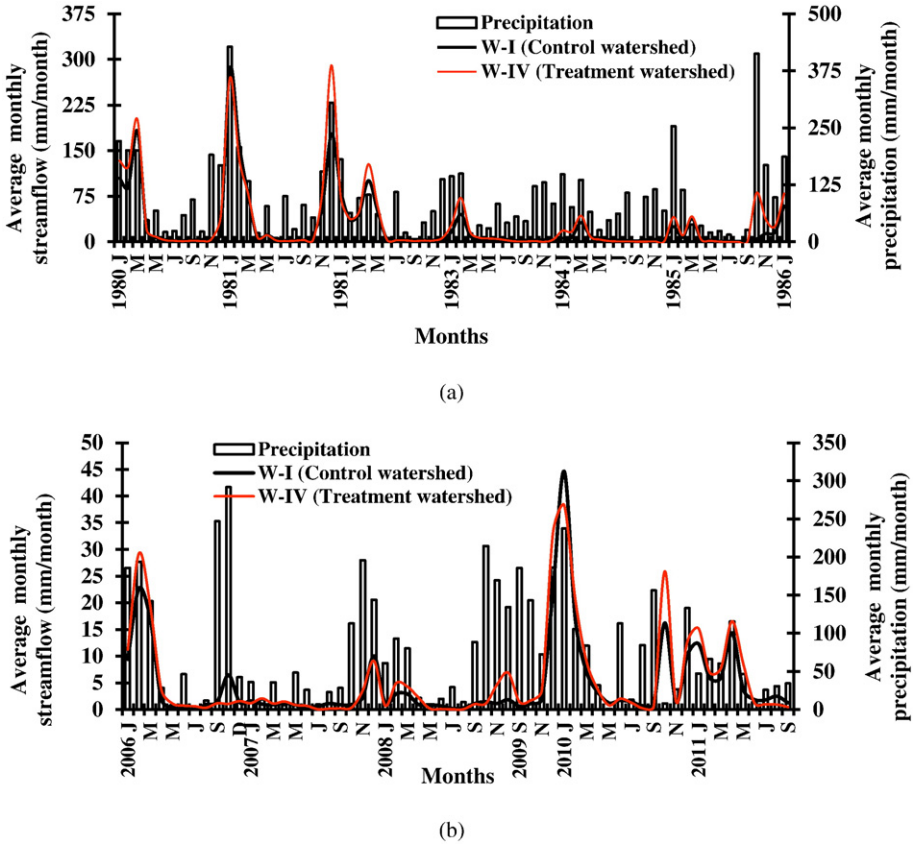

Fig. 2. Average monthly streamflow (mm) and precipitation (mm) during the calibration periods (a) 1980–1986 for 11% thinning and (b) 2006–2011 for 18% thinning treatments.

Table 3
Average monthly measured (W-IV_{MEA}) and estimated (W-IV_{EST}) streamflow values and differences (W-IV_{DIF}) in treatment watershed (W-IV).

Thinning intensity	Treatment periods (years)	W-IV_{MEA} average flow (mm)	W-IV_{EST} average flow (mm)	W-IV_{DIF} average flow (mm)	95% CI (upper/lower) for differences	Coefficient of correlation (r)/regression equations	Sign. of r/MSE
11%	Overall years	21.15	17.76	3.39	0.47/7.26	0.95/Y = 0.8813 * X + 0.3822	$p < 0.05$/0.17
	1986	15.86	10.09	5.77	−4.87/16.41	0.92/Y = 0.7352 * X + 0.4065	$p < 0.05$/0.14
	1987	29.61	25.53	4.08	−4.45/12.61	0.97/Y = 0.8475 * X + 0.5962	$p < 0.05$/0.25
	1988	34.60	28.61	5.99	−5.40/17.39	0.97/Y = 0.8843 * X + 0.4308	$p < 0.05$/0.18
	1989	3.65	5.53	−1.88	−3.48/−0.27	0.88/Y = 0.7974 * X + 0.2359	$p < 0.05$/0.11
18%	Over all years	16.26	14.71	1.56	−1.46/4.58	0.95/Y = 0.7428 * X + 0.2064	$p < 0.05$/0.06
	2012	14.38	12.66	1.72	−5.19/8.63	0.97/Y = 0.6769 * X + 0.3065	$p < 0.05$/0.09
	2013	10.80	11.57	−0.77	−3.18/1.64	0.95/Y = 0.8127 * X + 0.12	$p < 0.05$/0.04
	2014	21.17	14.91	6.26	−4.09/16.60	0.95/Y = 0.669 * X + 0.2154	$p < 0.05$/0.09
	2015	18.39	19.34	−0.95	−5.66/3.76	0.98/Y = 0.8645 * X + 0.1518	$p < 0.05$/0.02

model, the deviation from the observed and the predicted values could be indicated by the residuals. Residual plots were created to detect variance heterogeneity (unequal variance) and auto-correlated error (Fig. 3). This graphical technique was used for interpreting the normality, heteroscedasticity and independence of the regression model. The plots were generated by using log-transformed data.

The residuals plots did not show random distributions between the residuals. These plots showed uncorrelated residuals for both thinning treatments and time periods of the regression study. Heteroscedasticity was also observed in these cases (Fig. 3). This residual peak is probably due to the peak flow formed during the calibration and treatment periods.

Changes in estimated and measured monthly runoff values (mm) after timber harvest for the treatment watershed (W-IV) are presented in Fig. 4.

During the post treatment period, the peak flows occurred in January or February. The measured and estimated flows were similar throughout the treatment period, but large differences between predicted and measured runoff values were seen in the rainy winter months (Fig. 4).

3.2. Typical findings

Understanding the effects of treatments on runoff requires detailed and long-term watershed monitoring and analysis. Paired watershed studies have been widely used for this purpose (Bosch and Hewlett, 1982). Several studies have been carried out on afforestation (Cheng, 1999; McVicar et al., 2010), deforestation (Hibbert, 1967; Li et al., 2007; Thanapakpawin et al., 2007) and vegetation change (Zhou et al., 2008). Moreover, Zhang et al. (2011) reported that evapotranspiration was an effective parameter in streamflow response. Tables A.1 and A.2 summarize the results of several thinning and clearcutting studies in terms of changes in water yield.

In general, thinning treatments increased the water yield to some extent in these studies (Table A.1). Bosch and Hewlett (1982) associated the increase rate with harvesting area and thinning intensity, but found no linear relationship between intensity of timber harvest and water yield. However, it can be concluded that the highest increase in water yield occurred after clearcut treatments (Table A.2). In addition, Robinson et al. (1995) reported that watershed size was also an important parameter.

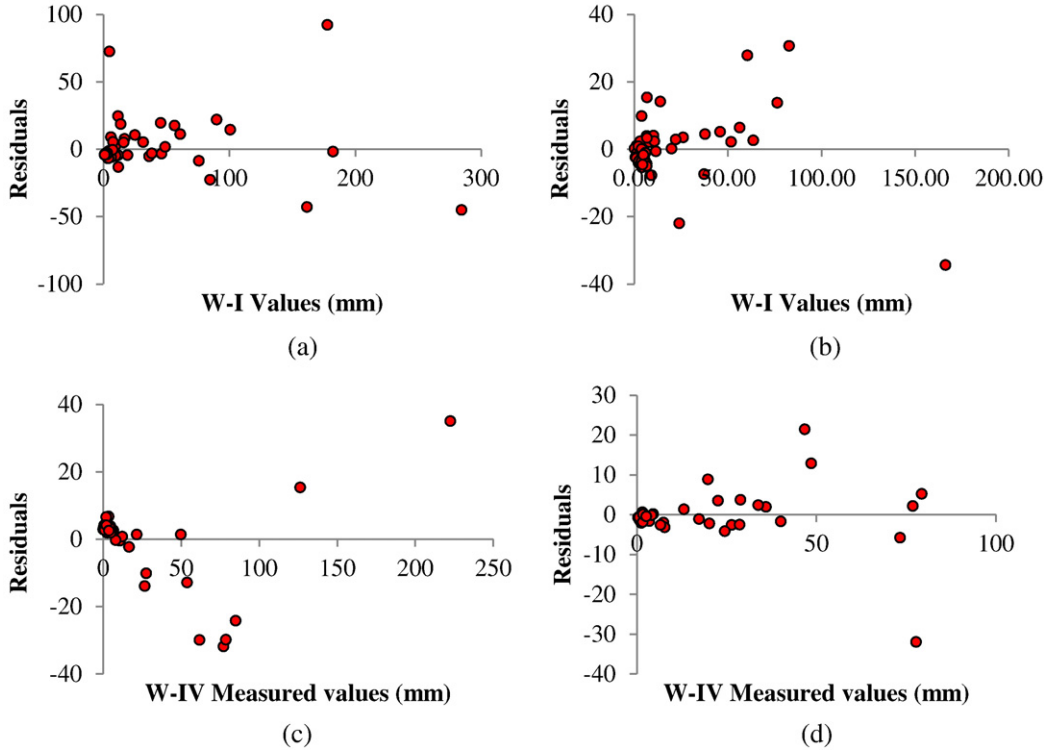

Fig. 3. (a) 11% thinning regression equations in calibration period; (b)18% thinning regression equations in calibration period; (c) 11% thinning regression equations in treatment period; (d) 18% thinning regression equations in treatment period.

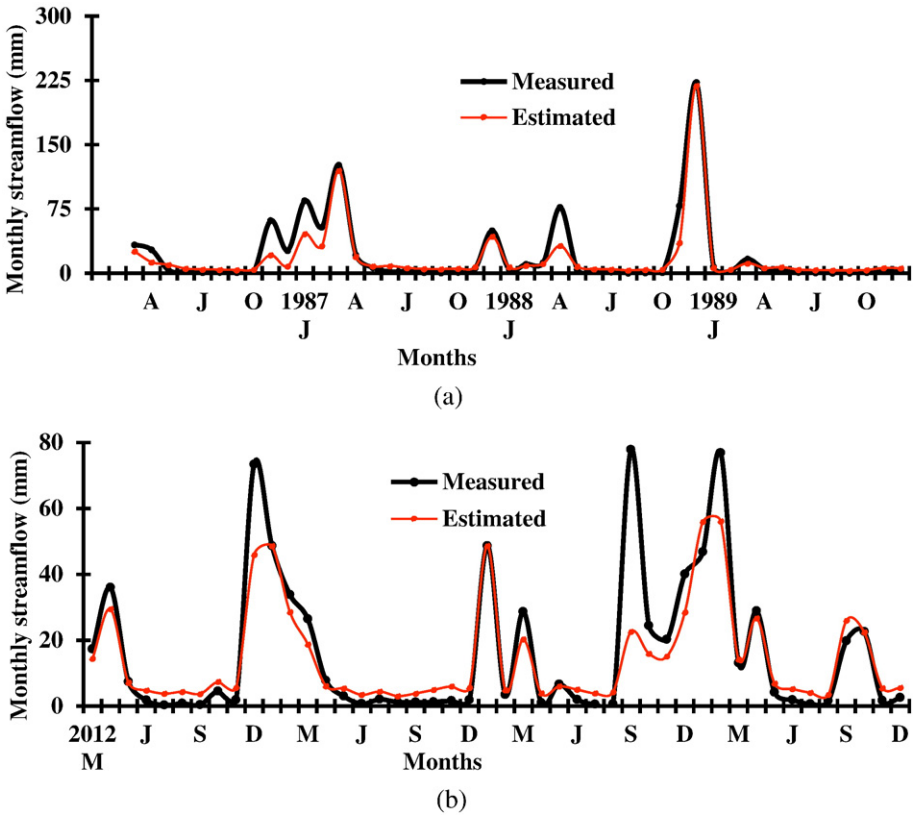

Fig. 4. Changes in measured and estimated runoff during the post-treatment period of (a) 11% and (b) 18% thinning treatments.

Clearcutting presents a more severe impact on the hydrology of watersheds. Thus, a more detectible effect on the streamflow is expected, as seen in the results of the experiments in Table A.2. In one experiment carried out in Japan, runoff increased 106 mm per year after a clearcut treatment, and runoff increased 525.2 mm per year after an 82% cut in the USA. Brown et al. (2005) noted that clearcutting or bushfire can cause rapid change in the streamflow over a period of days or weeks in small headwater catchments. Ganatsios et al. (2010) reported that clearcutting led to a 9.7% increase in water yield, whereas after a 50% thinning there was a 34.3% decline in interception. Moreover, Bréda et al. (1995) found that a 35% basal area removal caused a 30.4% decline in interception. Therefore, clearcutting can greatly produce a rapid increase in water yield compared to other harvesting techniques (e.g., thinning) because interception and transpiration are nearly suppressed.

Species conversion or conversion of the total ecosystem is another common forestry treatment that may affect the water yield. In Table A.3, the results of some vegetation change studies from around the world have been summarized.

Results of the vegetation change studies conducted in different countries showed that watershed hydrological characteristics were significantly affected by the type of vegetation cover (Table 6). For example, afforestation of grassland with Pinus and Larix species resulted in a reduction of 50–235 cm or more in annual streamflow (Buytaert et al., 2007; Rowe, 2003; Wang et al., 2008).

The influence of forestry treatments on streamflow varied according to the type and extent of the treatment and the ecological region in which it was implemented. Cutting treatments generally resulted in increases in runoff. The amount and duration of the increase was determined by the cutting intensity and the ecological conditions.

Through the end of the last century, watershed studies were concentrated on forestry practices and their effects on water quality and quantity, with particular emphasis on disturbances and removal of vegetation cover (Stednick and Troendle, 2016). However, the importance of runoff and the effects of minor thinning treatments on the forest hydrologic cycle have not been well documented (Bosch and Hewlett, 1982; Sahin and Hall, 1996). According to Stednick and Troendle (2016), after timber harvesting operations, an increase in water yield may not be detected in areas with <500 mm annual precipitation. In order to effect a change in streamflow, the intensity of the treatment should be above a certain threshold which is determined by the type of treatment, ecosystem and the ecological conditions. For example, Bosch and Hewlett (1982) claimed that at least 20% of the forest cover should be removed in order to detect increases in water yield. In other words, forest cover reductions of <20% were not expected to lead to a remarkable or detectable change in runoff. Similarly, Stednick (1996) concluded that a minimum of 20% of the forest cover must be harvested in order to effect a change in annual runoff. Contrary to these statements, Sahin and Hall (1996) reported that a 10% decrease in the forest cover was sufficient to cause a detectable change in the runoff. In addition to all this, the size of the watershed is a major determinant. Most paired catchment studies have been performed in small catchments of from 10 to a few hundred hectares. This has raised a debate on the validity of the results for mid- or large-sized watersheds because hydrologic systems, and especially runoff types (surface, subsurface and groundwater), are strongly affected by watershed size. The location and coverage of the treatment in a watershed are also linked with watershed size. In forestry, treatments are performed in limited areas. For example, there is an area limitation for clearcutting. A change in streamflow can be observed in the case of a 3–4 ha clearcut area in a small catchment, but this limited treatment can have very slight or no effect in a large watershed. Most of the studies on the impact of forest-cover changes on hydrology have been carried out using traditional paired watershed analysis. The results of some of these paired analyses have been summarized in a number of reviews (Bosch and Hewlett, 1982; Brown et al., 2005; Hibbert, 1967; Hornbeck et al., 1993; Sahin and Hall, 1996; Stednick, 1996). These literature reviews indicated that annual increases in water yield had occurred in the first year or first five years following treatment.

Streamflow responses to clearcutting activities are more drastic compared to responses to afforestation. Zhang et al. (2001) emphasized that evapotranspiration is the major component influencing water yield. When the vegetation is converted from forest to grassland in a watershed, the mean annual changes in water yield can be predicted from the changes in evapotranspiration. According to Zhang et al. (2001), maximum increases in water yield for forest vegetation are also likely to be driven by forest management activities that affect evapotranspiration.

Keppeler and Ziemer (1990) demonstrated that decreases in mean monthly precipitation caused reductions in the water yield and obscured the streamflow response to thinning intensity. Stednick (1996) verified this by reporting that high precipitation led to the greatest increases in water yield. However, the response of streamwaters depends not only on precipitation, but also on the attributes of the watershed including system memory. Soil moisture properties and parent material, vegetation and watershed size are all characteristics that determine the length of the hydrologic memory in the watersheds (Amenu et al., 2005).

4. Conclusion

Climate change may have significant influence on the hydrology of forested watersheds and this may result in a number of social, economic and ecological consequences. Forestry treatments can help mitigate adverse effects and support the provision of ecosystem resources. Harvesting, including clearcutting and thinning treatments, has long been suggested as a tool for increasing the runoff in a forested watershed. This study evaluated the possibility of using forestry treatments, cutting and vegetation change in this respect. The scientific evidence relies on experiments conducted worldwide, but particularly in North America. The results of some of these studies were merged with the findings of the present paired watershed study and it was concluded that runoff can be increased to a statistically significant level by light thinning treatments, but the amount of the increase may still remain far below an ecologically and economically significant level. Thus, at least 20% or more of the basal area should be removed by a cutting treatment in order to realize water production benefits. However, the treatment would be effective only in the case of a certain abundance of precipitation. It is not recommended to practice any cutting treatment that aims to increase water yield unless annual precipitation is over 400–500 mm since the role played by vegetation is less in arid regions and the water gained would be much lower. The present study results suggest that the watersheds responded in varying levels to the light cutting treatments, but generally with minimum water surplus.

The reason for the lower responses of the watersheds to the cutting treatments can be explained by the seasonality of the precipitation and the hydrologic system memory of the watersheds. Based on the literature on forest hydrology, it was concluded that the amount of water produced due to cutting treatments is affected by the amount of precipitation in the following months. Moreover, the previous months may also be important as streamflow is an output of several months of previous precipitation, especially in forested watersheds. This effect might be more significant in large watersheds considering the longer routing time of the water.

In terms of water production, conversion of vegetation and clearcutting are more drastic and effective treatments compared to partial or selective cutting. The reason for this lies in the duration needed by the ecosystem to restore itself. With clearcutting treatments, the duration of crown closure recovery may take more than one decade, even in temperate zones. This period can be two or three decades in cold climate regions at high altitudes. The crown cover is restored in one or two growing seasons in temperate climate zones, especially in the case of broadleaved species; therefore, the influence of the light cutting treatment is negated. The influence further disappears under arid summer conditions. According to the present results, the low precipitation in summer months inhibits the expected water surplus after a cutting treatment, while the influence of cutting can be low or disappear entirely in dormant seasons in broadleaved forests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.08.190.

References

Amenu, G.G., Kumar, P., Liang, X.Z., 2005. Interannual variability of deep-layer hydrologic memory and mechanisms of its influence on surface energy fluxes. J. Clim. 18, 5024–5045.

Asouti, E., Hather, J., 2001. Charcoal analysis and the reconstruction of ancient woodland vegetation in the Konya Basin, south-central Anatolia, Turkey: results from the Neolithic site of Çatalhöyük East. Veg. Hist. Archaeobotany 10, 23–32.

Balcı, A.N., Ozyuvacı, N., Ozhan, S., 1986. Sediment and nutrient discharge through streamflow from two experimental watersheds in natural oak-beech forest ecosytems near Istanbul, Turkey. J. Hydrol. 85, 31–47.

Balcı, A.N., Ozyuvacı, N., Ozhan, S., Sengonul, K., 1993. Calibration of paired experimental watersheds with respect to stream-flow characteristics in mature oak beech forest ecosystem near Istanbul-Turkey. Rev. Fac. For. Univ. Istanbul Ser. A 43, 13–32.

Belmar, O., Bruno, D., Martínez-Capel, F., Barquín, J., Velasco, J., 2013. Effects of flow regime alteration on fluvial habitats and riparian quality in a semiarid Mediterranean basin. Ecol. Indic. 30, 52–64.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E.L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T.M., Evans, L.S., Kotschy, K., Leitch, A.M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M.D., Schoon, M.L., Schultz, L., West, P.C., 2012. Toward principles for enhancing the resilience of ecosystem services. Annu. Rev. Environ. Resour. 37, 421–448.

Bosch, J.M., Hewlett, J.D., 1982. A review of watershed experiments to determine the effects of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55, 3–23.

Bozkurt, D., Sen, O.L., 2011. Precipitation in the Anatolian Peninsula: sensitivity to increased SSTs in the surrounding seas. Clim. Dyn. 36, 711–726.

Bréda, N., Granier, A., Aussenac, G., 1995. Effects of thinning on soil and tree water relations, transpiration and growth in an oak forest (*Quercus petraea* (Matt.) Liebl.). Tree Physiol. 15, 295–306.

Brown, A.E., Zhang, L., McMahon, T.A., Western, A.W., Vertessy, R.A., 2005. A review of paired watershed studies for determining changes in water yield resulting from alterations in vegetation. J. Hydrol. 310, 28–61.

Buytaert, W., Iniguez, V., De Bievre, B., 2007. The effects of afforestation and cultivation on water yield in the Andean páramo. For. Ecol. Manag. 251, 22–30.

Cheng, G., 1999. Forest change: hydrological effects in the upper Yangtze River valley. Ambio 28, 457–459.

De Dios, V.R., Fischer, C., Colinas, C., 2007. Climate change effects on Mediterranean forests and preventive measures. New For. 33, 29–40.

Ganatsios, H.P., Tsioras, P.A., Pavlidis, T., 2010. Water yield changes as a result of silvicultural treatments in an oak ecosystem. For. Ecol. Manag. 260, 1367–1374.

Gökbulak, F., Şengönül, K., Serengil, Y., Özhan, S., Yurtseven, İ., Uygur, B., Özçelik, M.S., 2016. Effect of forest thinning on water yield in a sub-humid Mediterranean oak-beech mixed forested watershed. Water Resour. Manag. 30, 5039–5049.

Hesse, C., Krysanova, V., Stefanova, A., Bielecka, M., Domnin, D.A., 2015. Assessment of climate change impacts on water quantity and quality of the multi-river Vistula Lagoon watershed. Hydrol. Sci. J. 60, 890–911.

Hibbert, A.R., 1967. Forest treatment effects on water yield. In: Sopper, W.E., Lull, H.W. (Eds.), Forest Hydrology. Pergamon, New York, N.Y.

Hornbeck, J.W., Adams, M.B., Corbett, E.S., Verry, E.S., Lynch, J.A., 1993. Long term impacts of forest treatments on water yield: a summary for northeastern USA. J. Hydrol. 150, 323–344.

IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (1535 pp).

Keppeler, E.T., Ziemer, R.R., 1990. Logging effects on streamflow: water yield and summer low flows at Caspar Creek in northwestern California. Water Resour. Res. 26, 1669–1679.

Laaha, G., Bloschl, G., 2006. Seasonality indices for regionalizing low flows. Hydrol. Process. 20, 3851–3878.

Li, K.Y., Coe, M.T., Ramankutty, N., Jong, R.D., 2007. Modeling the hydrological impact of land-use change. J. Hydrol. 337, 258–268.

Linder, M., 2000. Developing adaptive forest management strategies to cope with climate change. Tree Physiol. 20, 299–307.

Lionello, P., Abrantes, F., Gacic, M., Planton, S., Trigo, R., Ulbrich, U., 2014. The climate of the Mediterranean region: research progress and climate change impacts. Reg. Environ. Chang. 14, 1679–1684.

Mackey, B.G., Watson, J.E., Hope, G., Gilmore, S., 2008. Climate change, biodiversity conservation, and the role of protected areas: an Australian perspective. Biodiversitas 9, 11–18.

McVicar, T., Niel, T., Li, L., Wen, Z., Yang, Q., Li, R., Jiao, F., 2010. Parsimoniously modelling perennial vegetation suitability and identifying priority areas to support China's revegetation program in the Loess Plateau: matching model complexity to data availability. For. Ecol. Manag. 259, 1277–1290.

Ouarda, T.B.M.J., Cunderlik, J.M., St-Hilaire, A., Barbet, M., Bruneau, P., Bobée, B., 2006. Data-based comparison of seasonality-based regional flood frequency methods. J. Hydrol. 330, 329–339.
Özhan, S., 1977. Variation in Some Hydrologic Properties of Forest Floor as Related to Certain Environmental Factors in Ortadere Watershed of Belgrad Forest. Publication of Istanbul University, Faculty of Forestry Publication. 235 p. 179 (Istanbul).
Özhan, S., Gökbulak, F., Serengil, Y., Özcan, M., 2010. Evapotranspiration from a mixed deciduous forest ecosystem. Water Resour. Manag. 24, 2353–2363.
Pamukcu, P., Serengil, Y., Yurtseven, I., 2014. Role of forest cover, land use change and climate change on water resources in Marmara basin of Turkey. iForest 8, 480.
Pawson, S.M., Brin, A., Brockerhoff, E.G., Lamb, D., Payn, T.W., Paquette, A., Parrotta, J.A., 2013. Plantation forests, climate change and biodiversity. Biodivers. Conserv. 22, 1203–1227.
Rammer, W., Seidl, R., 2015. Coupling human and natural systems: simulating adaptive management agents in dynamically changing forest landscapes. Glob. Environ. Chang. 35, 475–485.
Robichaud, P.R., 2016. Hydrology of Forests after Wildfire. Forest Hydrology: Processes, Management and Assessment, CABI, Wallingford.
Robinson, J.S., Sivapalan, M., Snell, J.D., 1995. On the relative roles of hillslope processes, channel routing, and network geomorphology in the hydrologic response of natural catchments. Water Resour. Res. 31, 3089–3101.
Rowe, L.K., 2003. Land Use and Water Resources: A Comparison of Streamflow From New Zealand Watersheds With Different Vegetation Covers. Landcare Research Contract Report 6. Landcare Research, Lincoln.
Roy, A.H., Freeman, M.C., Freeman, B.J., Wenger, S.J., Ensign, W.E., Meyer, J.L., 2005. Investigating hydrologic alteration as a mechanism of fish assemblage shifts in urbanizing streams. J. N. Am. Benthol. Soc. 24, 656–678.
Sahin, V., Hall, M.J., 1996. The effects of afforestation and deforestation on water yields. J. Hydrol. 178, 293–309.
Sanz, D.B., del Jalón, D.G., 2005. Characterisation of streamflow regimes in central Spain, based on relevant hydrobiological parameters. J. Hydrol. 310, 266–279.
Serengil, Y., Gökbulak, F., Özhan, S., Hızal, A., Şengönül, K., Balcı, A.N., Özyuvacı, N., 2007. Hydrological impacts of a slight thinning treatment in a deciduous forest ecosystem in Turkey. J. Hydrol. 333, 569–577.
Serengil, Y., Swank, W.T., Vose, J.M., 2012. Alterations on flow variability due to converting hardwood forests to pine. IForest 5, 44.
Sicard, P., Augustaitis, A., Belyazid, S., Calfapietra, C., de Marco, A., Fenn, M., Bytnerowicz, A., Grulke, N., Serengil, Y., 2016. Global topics and novel approaches in the study of air pollution, climate change and forest ecosystems. Environ. Pollut. 213, 977–987.
Ssegane, H., Amatya, D.M., Muwamba, A., Chescheir, G.M., Appelboom, T., Tollner, E.W., Nettles, J.E., Youssef, M.A., Birgand, F., Skaggs, R.W., 2015. Hydrologic calibration of paired watersheds using a MOSUM approach. Hydrol. Earth Syst. Sci. Discuss. 12, 245–279.
Stankey, G.H., Clark, R.N., Bormann, B.T., 2005. Adaptive management of natural resources: theory, concepts, and management institutions. Gen. Tech. Rep. PNW-GTR-654. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station (73 p).
Stednick, J.D., 1996. Monitoring the effects of timber harvest on annual water yield. J. Hydrol. 176, 79–95.
Stednick, J.D., Troendle, C.A., 2016. Hydrological Effects of Forest Management. Forest Hydrology: Processes, Management and Assessment, CABI, UK.
Thanapakpawin, P., Richey, J., Thomas, D., Rodda, S., Campbell, B., Logsdon, M., 2007. Effects of landuse change on the hydrologic regime of the Mae Chaem river basin, NW Thailand. J. Hydrol. 334, 215–230.
Wang, Y., Yu, P., Xiong, W., Shen, Z., Guo, M., Shi, Z., Du, A., Wang, L., 2008. Water-yield reduction after afforestation and related processes in the semiarid Liupan Mountains, Northwest China. J. Am. Water Resour. Assoc. 44, 1086–1097.
Xiang, H., Zhang, Y., Richardson, J.S., 2016. Importance of riparian zone: effects of resource availability at land-water interface. Rip. Ecol. Conserv. 3, 1–17.
Zhang, L., Dawes, W.R., Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour. Res. 37, 701–708.
Zhang, Y., Liu, S., Gu, F., 2011. The impact of forest vegetation change on water yield in subalpine region of southwestern China. Acta Ecol. Sin. 31, 7601–7608.
Zhou, P., Luukkanen, O., Tokola, T., Nieminen, J., 2008. Vegetation dynamics and forest landscape restoration in the Upper Min River watershed, Sichuan, China. Restor. Ecol. 16, 348–358.